

Applications of OpenLoops to Top and Higgs Phenomenology

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based on

F. Cascioli, P. Maierhöfer and S.P., PRL **108** (2012) [arXiv:1111.5206]

F. Cascioli, P. Maierhöfer, N. Moretti, S. P. and F. Siegert, EPJ **C74** (2014)
[arXiv:1309.5912]

F. Cascioli, S. Kallweit, P. Maierhöfer and S. P., PLB (2014) [arXiv:1312.0546]

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Outline of the Talk

- (A) NLO revolution, automation and **OpenLoops**
- (B) Unified NLO description of $t\bar{t}$ and Wt production
- (C) S-MC@NLO matching for $t\bar{t}b\bar{b}$ production in the 4F scheme

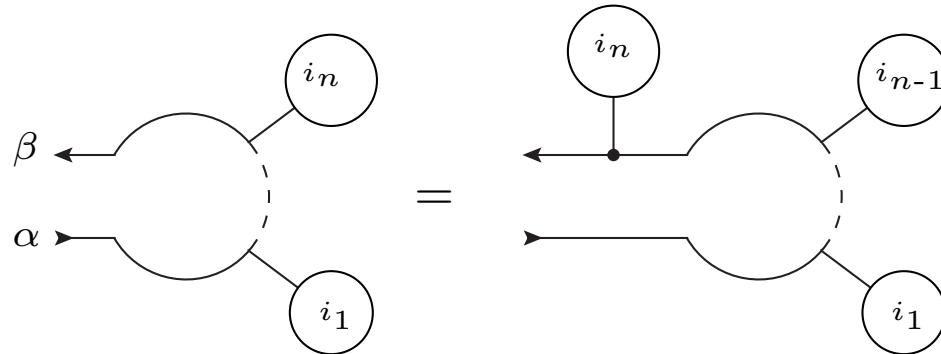
(A) NLO Multi-particle Revolution and Automation

NLO QCD calculations for $2 \rightarrow 4(5,6)$ processes at the LHC

- many recent results (since 2009): $5j$, $W + 5j$, $Z + 4j$, $H + 3j$, $WWjj$, $WZjj$, $\gamma\gamma + 3j$, $W\gamma\gamma j$, $WWb\bar{b}$, $b\bar{b}b\bar{b}$, $t\bar{t}b\bar{b}$, $t\bar{t}jj$, $t\bar{t}t\bar{t}$, ...
- NLO wish list closed since $2 \rightarrow 4$ NLO feasibility well established but physics content of wish-list (and other) processes far from being fully explored (see this talk)

Automation of NLO simulations (including matching and merging!)

- many NLO tools: `CutTools`, `Samurai`, `HELAC-NLO`, `MadLoop`, `GoSam`, `BlackHat`, `Ninja`, `NJet`, `OpenLoops`, `Collier`, `Recola`, `Madgraph/aMC@NLO`, `POWHEG`, `Sherpa`, `Herwig`, `Pythia`
- but plenty of nontrivial physical and technical aspects (multiple scales, resonances,...) that require grain of salt (not just running the tools)
- great potential to promote NLO to standard TH accuracy at LHC but further efficiency improvements crucial for most challenging processes



The OpenLoops Algorithm [Cascioli, Maierhöfer, S.P '11]

$$\sum_{r=0}^n \mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^{\beta}(\mathcal{I}_n) q^{\mu_1} \dots q^{\mu_r} = (Y_{\gamma\delta}^{\beta} + q^{\nu} Z_{\nu;\gamma\delta}^{\beta}) \sum_{r=0}^{n-1} \mathcal{N}_{\mu_1 \dots \mu_r; \alpha}^{\beta}(\mathcal{I}_{n-1}) q^{\mu_1} \dots q^{\mu_r}$$

meanwhile implemented also in MADGRAPH5_AMC@NLO

Hybrid “tree–loop” recursion

- open loops = trees with loop-momentum flow information
- generated with numerical recursion that merges open loops and external trees
- original Dyson-Schwinger formulation [van Hameren '09] transposed to Feynman diagrams \Rightarrow powerful tricks from colour/helicity/loop-momentum separation
- full automation with tensor reduction or OPP reduction (huge speed up)

OpenLoops and Monte Carlo Generators

OpenLoops [Cascioli, Maierhöfer, S.P., (2012)]

- very fast and fully flexible (kernels depend only on Lagrangian)
- NLO QCD automation up to $2 \rightarrow 4(5)$ SM processes

Two alternatives for reduction to scalar integrals

- tensor integrals with COLLIER [Denner, Dittmaier, Hofer] (Gram-det expansions)
- OPP reduction with CUTTOOLS [Ossola, Papadopolous, Pittau '07] or SAMURAI [Mastrolia, Ossola, Reiter, Tramontano '10]

Complete NLO automation through interface with NLO Monte Carlo Tools

- Sherpa2.1 [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Zapp] used for $t\bar{t}bb$
⇒ automated S-MC@NLO matching to SHERPA parton shower and MEPS@NLO multi-jet merging
- parton-level Monte-Carlo by S. Kallweit used for $WWbb$
⇒ fully automated and very fast fixed-order MC integrator
- BLHA interface

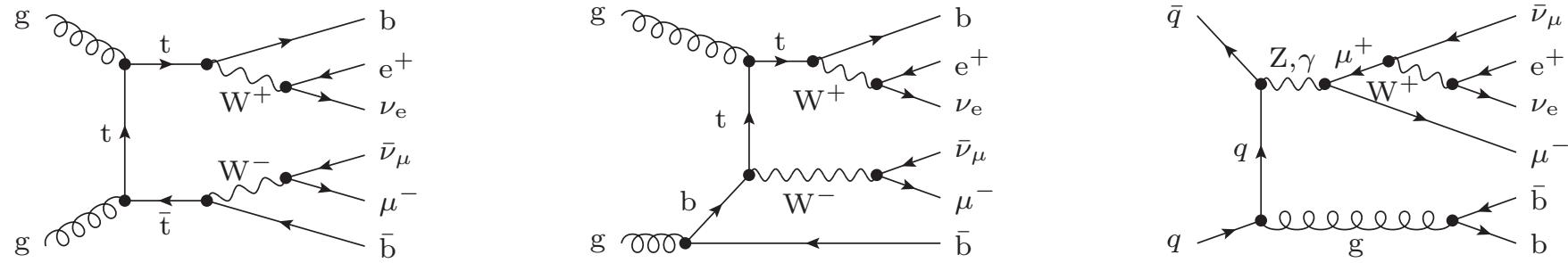
First OpenLoops Applications (Higgs and Top phenomenology)

- MEPS@NLO for $\ell\ell\nu\nu+0,1$ jets, Cascioli, Höche, Krauss, Maierhöfer, S. P. , Siegert, arXiv:1309.0500
- MC@NLO $pp \rightarrow t\bar{t}b\bar{b}$ with $m_b > 0$, Cascioli, Maierhöfer, Moretti, S. P. , Siegert, arXiv:1309.5912
- NLO for $pp \rightarrow W^+W^-b\bar{b}$ with $m_b > 0$, Cascioli, Kallweit, Maierhöfer, S. P., arXiv:1312.0546
- NNLO for $pp \rightarrow \gamma Z$ production, Grazzini, Kallweit, Rathlev, Torre, arXiv:1309.7000
- NLO merging for $pp \rightarrow HH+0,1$ jets, Maierhöfer, Papaefstathiou, arXiv:1401.0007
- MEPS@NLO for $t\bar{t}+0,1,2$ jets, Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert arXiv:1402.6293
- MEPS@NLO for $WWW+0,1$ jets, Höche, Krauss, S. P. , Schönherr, Thompson arXiv:1403.7516
- NNLO for $q\bar{q} \rightarrow t\bar{t}$ production, Abelof, Gehrmann–de Ridder, Maierhöfer, S.P. , arXiv:1404.6493
- NNLO for $pp \rightarrow ZZ$ production, Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P. , Rathlev, Tancredi, Weihs, arXiv:1405.2219

Technical Motivation

- technical stress tests: multi-particle and multi-scale problems, loop-induced processes, multiple resonances, ...
- beyond parton-level NLO: MC@NLO, MEPS@NLO and NNLO applications

(B) Unified NLO Description of $t\bar{t}$ and Wt Production+Decay [Cascioli,Kallweit,Maieröfer,S.P. '13]



$pp \rightarrow W^+W^-b\bar{b}$ in 5F scheme [Denner,

Dittmaier, Kallweit, S.P. '10; Bevilacqua et al. '10;
Heinrich et al. '13; Kardos et al. '14]

- off-shell, single- and non-resonant contributions ($\mu_t^2 = m_t^2 - i\Gamma_t m_t$)
- small $\mathcal{O}(\Gamma_t/m_t)$ effects with $t\bar{t}$ cuts
- $m_b = 0$ approx. requires two hard b-jets ($g \rightarrow b\bar{b}$ collinear singularities)

$pp \rightarrow W^+W^-b\bar{b}$ in 4F scheme ($m_b > 0$)

[Frederix'13; Cascioli,Kallweit,Maieröfer,S.P. '13]

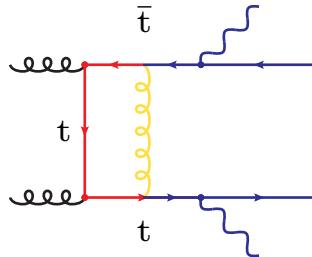
- off-shell $WW \rightarrow \ell\ell\nu\nu$ decays

- full b-quark phase space
- important for top-backgrounds in 0- and 1-jet bins (e.g. in $H \rightarrow WW$)
- first consistent $t\bar{t}$ and Wt combination with interference at LO and NLO
- avoids separation of Wt from $t\bar{t}$ in 5F scheme (unstable and ill-defined due to $t\bar{t}$ contamination at NLO)

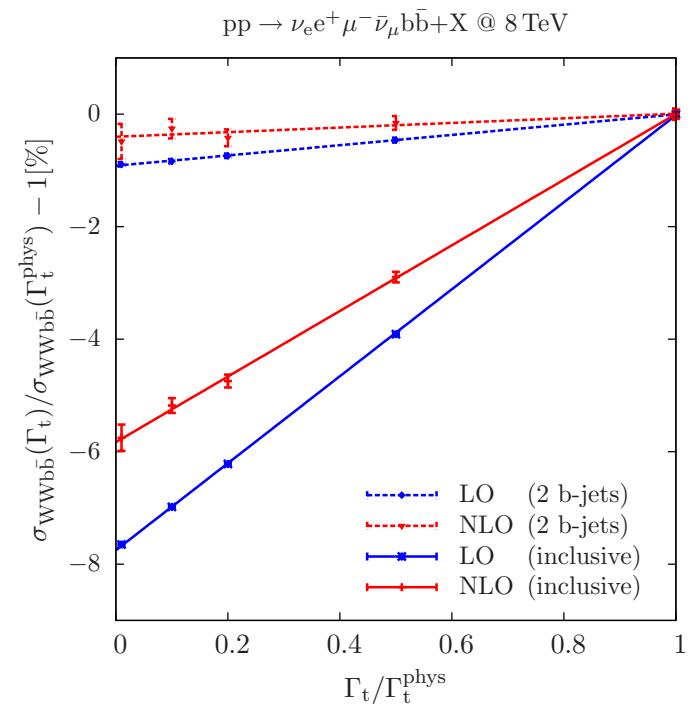
III-defined $t\bar{t}/Wt$ Separation in 5F Scheme \Rightarrow Gauge-invariant $t\bar{t}$ /non- $t\bar{t}$ Separation

Numerical NWA \Rightarrow on-shell $t\bar{t}$ production \times decay

$$d\sigma_{t\bar{t}} = \lim_{\Gamma_t \rightarrow 0} \left(\frac{\Gamma_t}{\Gamma_t^{\text{phys}}} \right)^2 d\sigma_{W+W-b\bar{b}}(\Gamma_t)$$



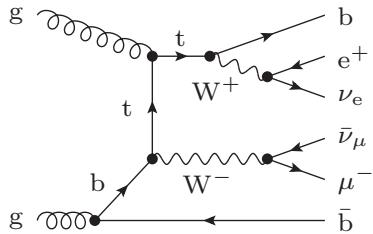
permille-level convergence shows
cancellation of soft-gluon $\ln(\Gamma_t/m_t)$
singularities



Finite-top-width remainder (FtW)

- contains all $\mathcal{O}(\Gamma_t/m_t)$ effects: off-shell $t\bar{t}$ production, single-top and non-resonant contributions with interferences
- from sub-percent for 2 b-jet final states to 6–8% effect in inclusive case (and more for 0/1-jets!)

Dynamic Scale Choice for Multi-channel/Multi-scale Nature of $W^+W^-b\bar{b}$



Idea: $\mu_R \sim m_t$ for $g \rightarrow b\bar{b}$ splittings might generate corrections up to $\alpha_S(m_b)/\alpha_S(m_t) \sim 2$ in Wt contribution

Appropriate scales for $t\bar{t}$ and Wt production (see CKKW and AP evolution)

$$\mu_{t\bar{t}}^2 = E_{T,t} E_{T,\bar{t}} \quad \mu_{tW^-}^2 = E_{T,t} E_{T,\bar{b}} \quad \Rightarrow \quad \alpha_S^2(\mu_{tW^-}^2) \simeq \alpha_S(E_{T,t}^2) \alpha_S(E_{T,\bar{b}}^2)$$

Global “interpolating scale”

$$\mu_{WWbb}^2 = \mu_{W+b} \mu_{W-\bar{b}} \quad \text{with} \quad \mu_{Wb} = P_b(p_{W,b}) E_{T,b} + P_t(p_{W,b}) E_{T,t}$$

$g \rightarrow b\bar{b}$ and $t \rightarrow Wb$ **probabilities dictated by** respective **singularity structures**

$$\frac{P_b}{P_t} \propto \frac{\chi_b}{\chi_t} \quad \text{with} \quad \chi_b = \frac{m_t^2}{E_{T,b}^2}, \quad \chi_t = \frac{m_t^4}{[(p_W + p_b)^2 - m_t^2]^2 + \Gamma_t^2 m_t^2},$$

and free constants fixed by **natural normalisation conditions**

$$P_b + P_t = 1, \quad \text{and} \quad \int d\sigma_{W^+W^-b\bar{b}}^{FtW} = \int d\Phi [1 - P_t(\Phi)P_{\bar{t}}(\Phi)] \frac{d\sigma_{W^+W^-b\bar{b}}}{d\Phi}$$

Consistency of $t\bar{t}$ vs tW Probability Densities

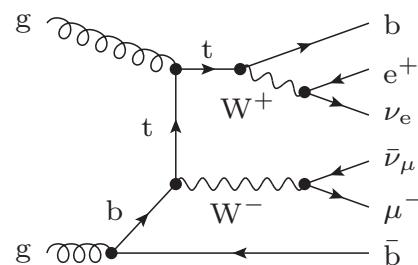
Check normalisation identity for more exclusive/differential observables

$$\int d\sigma_{W^+W^-b\bar{b}}^{\text{FtW}} = \int d\Phi [1 - P_t(\Phi)P_{\bar{t}}(\Phi)] \frac{d\sigma_{W^+W^-b\bar{b}}}{d\Phi}$$

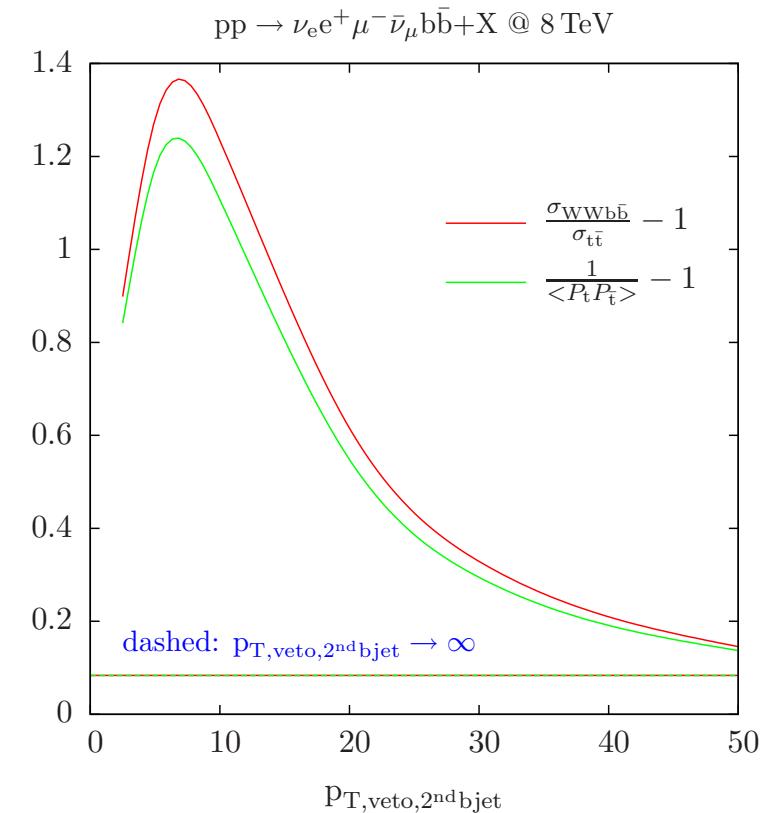
to verify if observed **finite-top-width effects** (computed via $\Gamma_t \rightarrow 0$) are **consistent with (pseudo)probability densities**

Test dependence wrt veto on 2nd b-jet

- single-top Wt contribution strongly enhanced when $p_{T,\text{veto}} \rightarrow 0$



- enhancement fairly well described by $P_t(\Phi), P_b(\Phi)$ probability densities



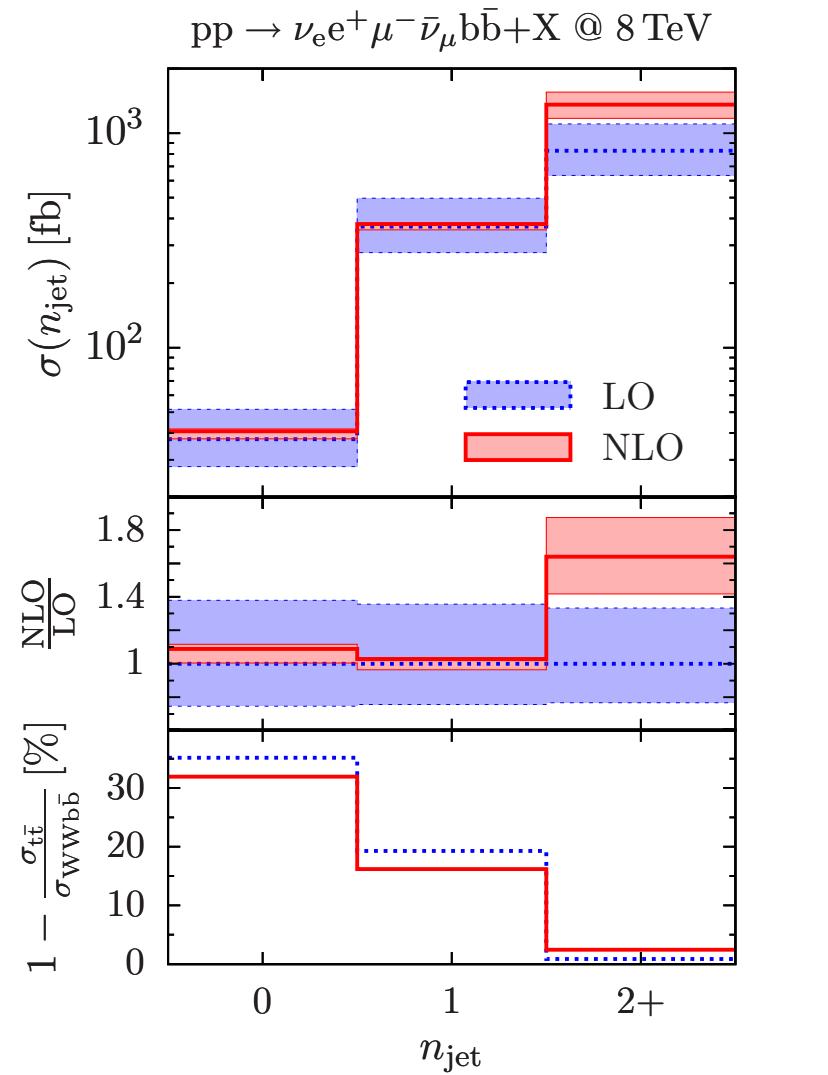
NLO and FtW Effects in Jet Bins

Jet bins relevant for $t\bar{t}$ -suppression and most interesting application of $m_b > 0$

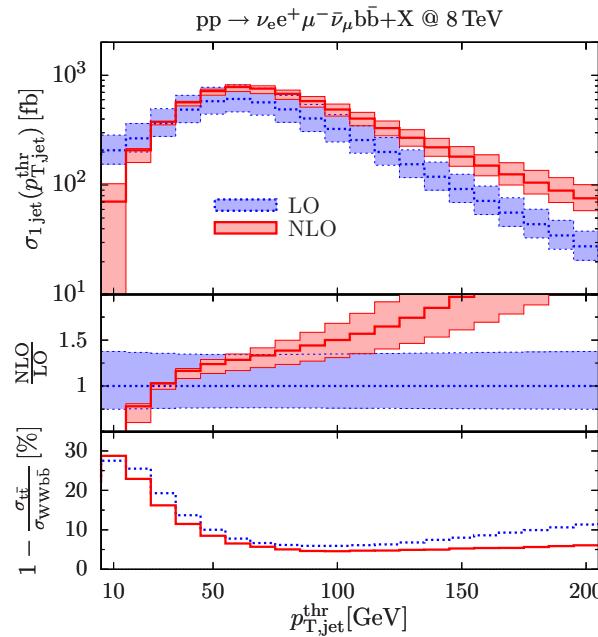
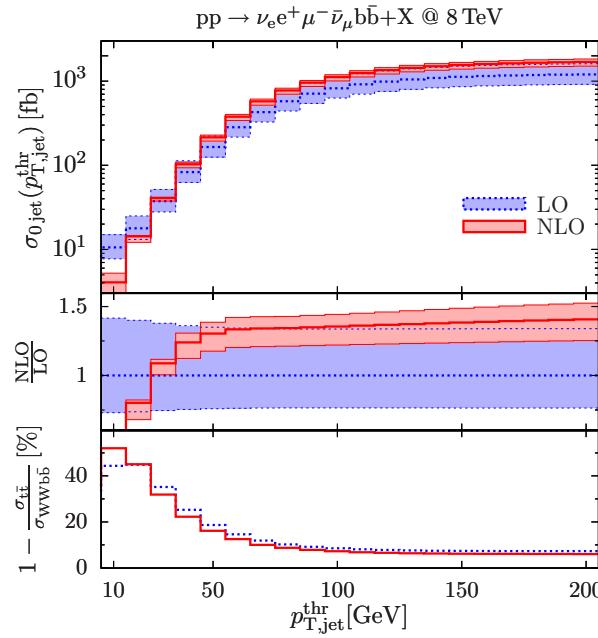
- 40% inclusive NLO correction driven by 2-jet bin, with very stable 0/1-jet bins
- only $\sim 10\%$ NLO uncertainty in all bins!
- **FtW contribution** bin-dependent (2% to 30%) and **strongly enhanced in 0/1-jet bins!**
- also FtW part perturbatively stable (not shown here)

Success of “ad-hoc” scale choice

- but naive $\mu = m_t$ choice yields surprisingly similar stability in jet bins!
- “ad-hoc scale” should be superior for more exclusive observables...



NLO(LO) 4F NNPDFSS, $p_{T,j} = 30$ GeV



Jet-Veto and Binning Effects

0-jet bin vs p_T -veto

- smooth inclusive limit at large p_T and very strong p_T sensitivity below 50 GeV:
 - FtW effects increase up to 50%
 - K -factor falls very fast
- at low p_T IR singularity calls for NLO+PS matching
- typical veto $p_T \sim 30 yields 98% suppression and still decent NLO stability ($K \sim 1$)$

1-jet bin vs p_T threshold

- low p_T behaviour driven by veto on 2nd jet and analogous to 0-jet case
- high p_T region driven by 1st jet and NLO radiation dominates over b-jets from $W^+W^-b\bar{b}$

Nontrivial interplay of NLO and off-shell/single-top effects

(B) S-MC@NLO $t\bar{t}b\bar{b}$ 4F Simulation [Cascioli, Maieröfer, Moretti, S.P., Siegert '13]

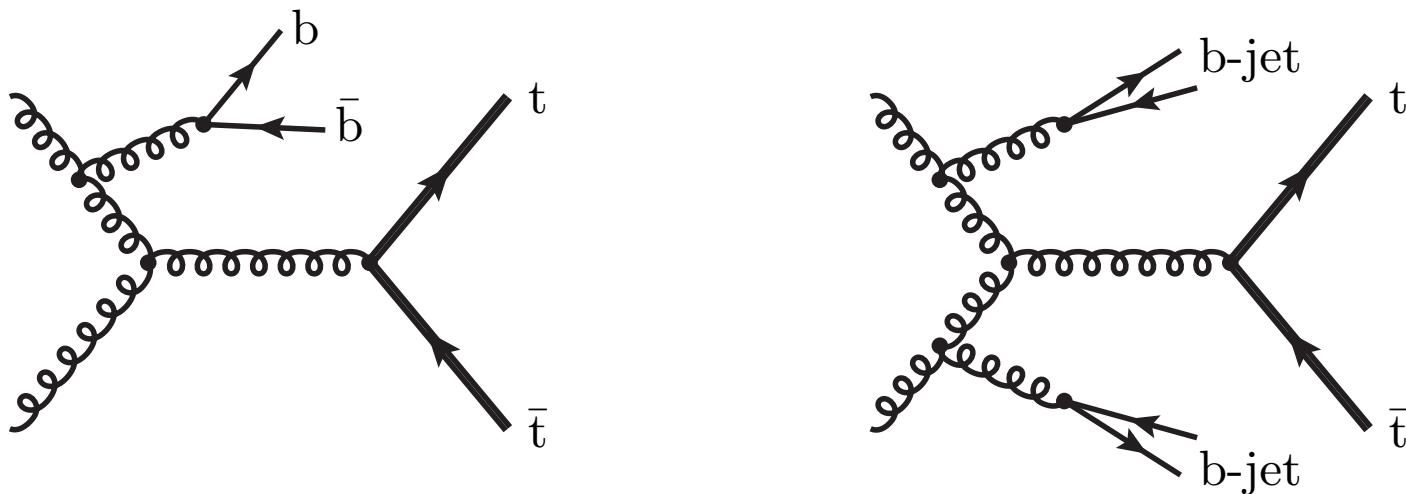
Importance of precise $t\bar{t}b\bar{b}$ predictions for $t\bar{t}H(b\bar{b})$ searches

- ATLAS/CMS can only exclude $4\text{--}5 \times \sigma_{t\bar{t}H}^{\text{SM}}$ and TH uncertainty of irreducible $t\bar{t}b\bar{b}$ background crucial to improve sensitivity
- NLO calculations reduce error from 80% to 20–30% [Bredenstein, Denner, Dittmaier, S. P. '09/'10; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]
- ATLAS/CMS analyses require matching to PS

NLO+PS $t\bar{t}b\bar{b}$ simulations with different matching, PS and b-quark treatment

- POWHEG matching to Pythia/Herwig, 5F-scheme ($m_b = 0$) [Kardos, Trocanyi '13]
- S-MC@NLO matching to Sherpa, 4F-scheme (finite m_b)
[Cascioli, Maieröfer, Moretti, S.P., Siegert '13]

Why NLO Matching for $t\bar{t}b\bar{b}$ Production in 4F (and not 5F) Scheme



5F scheme ($m_b = 0$): $t\bar{t}b\bar{b}$ MEs cannot describe collinear $g \rightarrow b\bar{b}$ splittings

- ⇒ *inclusive $t\bar{t}+b$ -jets simulation* (quite important for exp. analyses!) requires $t\bar{t}g+PS$,
i.e. $t\bar{t}+ \leq 2$ jets NLO merging [Höche, Krauss, Maierhöfer, S. P., Schönherr, Siegert '14]
see talk by F. Krauss

4F scheme ($m_b > 0$): $t\bar{t}b\bar{b}$ MEs cover full b-quark phase space

- ⇒ MC@NLO $t\bar{t}b\bar{b}$ sufficient for inclusive $t\bar{t}+b$ -jets simulation
- access to **new $t\bar{t} + 2b$ -jets production mechanism** wrt 5F scheme: **double collinear $g \rightarrow b\bar{b}$ splittings** (surprisingly important impact on $t\bar{t}H(b\bar{b})$ analysis!)

Sherpa's MC@NLO master formula [Frixione, Webber '02; Höche, Krauss, Schönherr, Siegert '11]

$$\begin{aligned}\sigma_n^{\text{MC@NLO}} = & \int d\Phi_n \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \mathcal{B}(\Phi_n) \otimes \mathcal{T} \right] \left\{ \Delta(\mu_Q^2, t_{\text{IR}}) + \int_{t_0}^{\mu_Q^2} d\Phi_1 \mathcal{S}(\Phi_1) \Delta(\mu_Q^2, t) \right\} \\ & + \int d\Phi_{n+1} \left[\mathcal{R}(\Phi_{n+1}) - \mathcal{B}(\Phi_n) \otimes \mathcal{S}(\Phi_1) \right]\end{aligned}$$

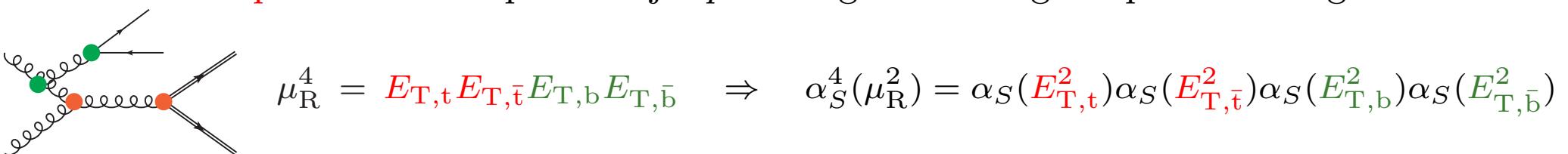
- shower resummation effectively acts starting from $\mathcal{O}(\alpha_s^2)$, and iterated emissions yield fully realistic events
- inclusive observables with n ($n+1$) particles preserve NLO (LO) accuracy

Factorisation and Resummation scales (available phase space for QCD emission)

$$\mu_F = \mu_Q = \frac{1}{2}(E_{T,t} + E_{T,\bar{t}})$$

Scale choice crucial due to $\alpha_S^4(\mu^2)$ dependence (80% LO variation)

- widely separated scales $m_b \leq Q_{ij} \lesssim m_{t\bar{t}b\bar{b}}$ can generate huge logs
- CKKW inspired scale adapts to b-jet p_T and guarantees good pert. convergence



NLO Corrections and Uncertainties for $t\bar{t}b$ and $t\bar{t}bb$ Cross Sections

Analyses with $N_b \geq 1$ ($t\bar{t}b$) and $N_b \geq 2$ ($t\bar{t}bb$) QCD b-jets ($p_T > 25$ GeV, $|\eta| < 2.5$)

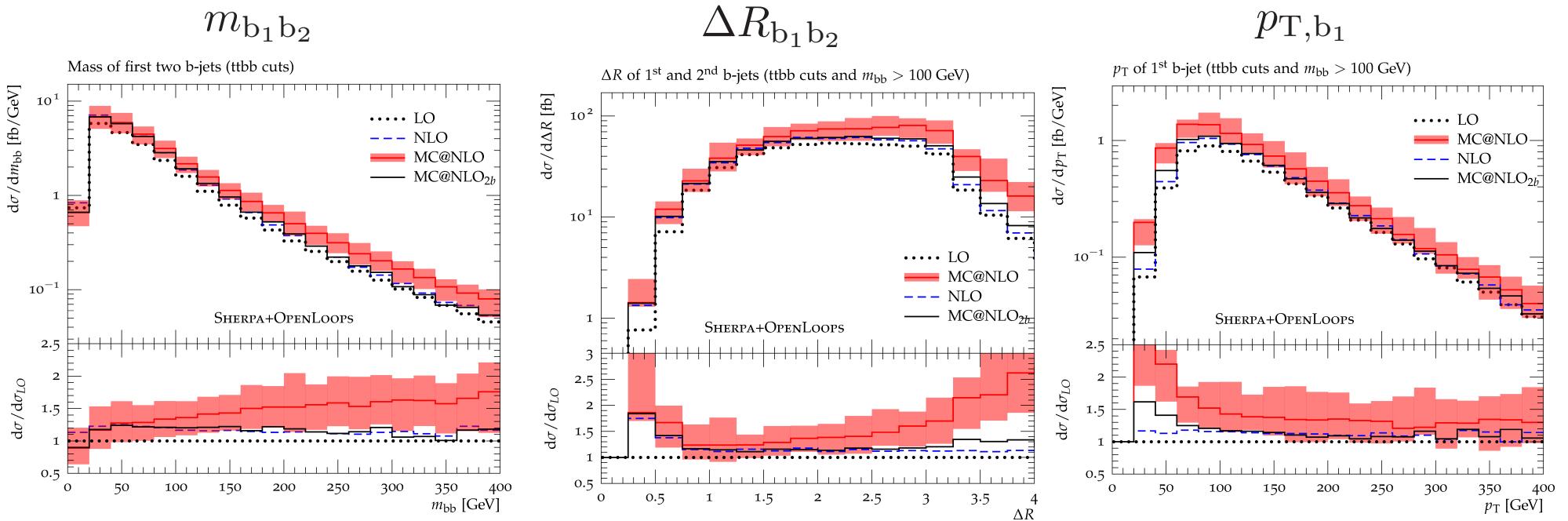
	$t\bar{t}b$	$t\bar{t}bb$	$t\bar{t}bb (m_{b\bar{b}} > 100)$
$\sigma_{\text{LO}} [\text{fb}]$	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
$\sigma_{\text{NLO}} [\text{fb}]$	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
$\sigma_{\text{NLO}}/\sigma_{\text{LO}}$	1.25	1.21	1.15
$\sigma_{\text{MC@NLO}} [\text{fb}]$	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{\text{MC@NLO}}/\sigma_{\text{NLO}}$	1.01	1.07	1.28

MSTW2008 NLO(LO) 4F PDFs

Good perturbative stability but unexpected MC@NLO enhancement

- K -factors moderate and rather independent of selection (including $t\bar{t}b$!)
- 25–30% NLO and MC@NLO uncertainties mainly from μ_R (1st) variation, only 5% from μ_F, μ_Q (2nd) variations
- MC@NLO/NLO difference is negligible(moderate) in standard $t\bar{t}b(t\bar{t}bb)$ selections but large enhancement ($\sim 30\%$) in Higgs-signal region ($m_{b\bar{b}} > 100$ GeV)

NLO and MC@NLO Effects in Distributions ($t\bar{t}bb$ Selection)



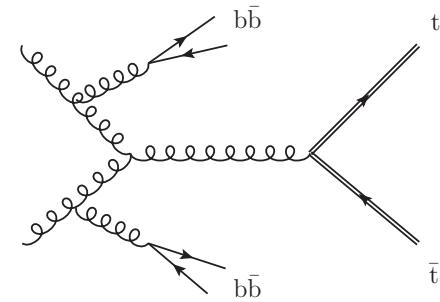
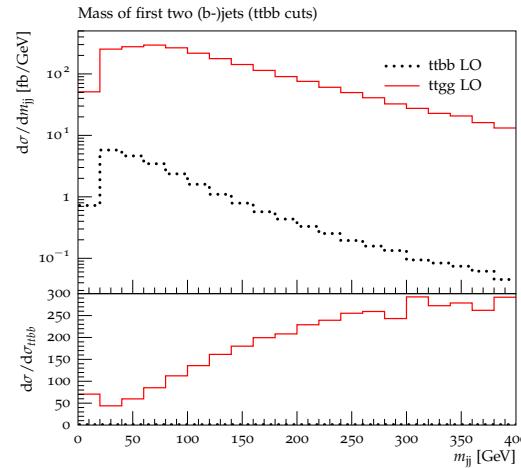
Characteristic kinematic features

- NLO corrections quite flat
- **MC@NLO enhancement at large $m_{b_1 b_2}$, $\Delta R_{b_1 b_2} \sim \pi$, and small $p_{T,b}$**
- reaches 25–30% at $m_{b_1 b_2} \sim 125$ GeV, which **exceeds $t\bar{t}H(b\bar{b})$ signal!**
- disappears almost completely in MC@NLO_{2b} where $g \rightarrow b\bar{b}$ splittings are switched off in the parton shower (**double $g \rightarrow b\bar{b}$ splittings “smoking gun”**)

Double $g \rightarrow b\bar{b}$ Splitting Contributions

Consistent with MC enhancement

- $t\bar{t}gg/t\bar{t}bb$ ratio grows at same rate of MC@NLO excess
- emission of back-to-back small- p_T gluons enhanced by soft-collinear singularity



Don't fit into conventional hard-scattering $t\bar{t}bb$ picture

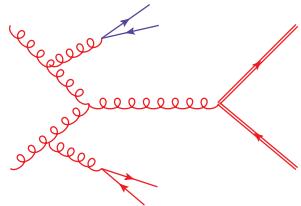
- present also in $t\bar{t}+{\rm jets}$ LO merged samples
- but large effect in hard $t\bar{t}H(b\bar{b})$ signal region unexpected

Implications for theory systematics in $t\bar{t}+{\rm HF}$

- understanding PS systematics crucial (both for 4F $t\bar{t}bb$ or 5F $t\bar{t}+{\rm jets}$)
- in $t\bar{t}H(b\bar{b})$ signal region 4F $t\bar{t}bb$ MC@NLO provides first $g \rightarrow b\bar{b}$ splitting at NLO

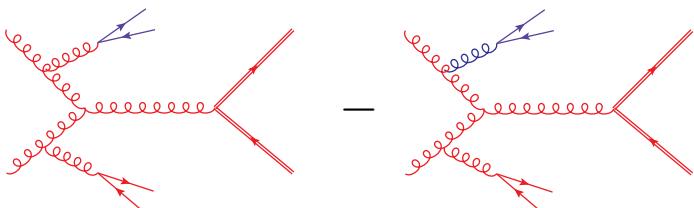
Accuracy of “Double Splittings” in MC@NLO $t\bar{t}bb$ Simulation

Naive picture



real-emission $t\bar{t}b\bar{b}g$ MEs plus $g \rightarrow b\bar{b}$ shower splitting
⇒ only LO+PS accuracy as in usual LO merging

Correct MC@NLO picture: interplay of three different contributions

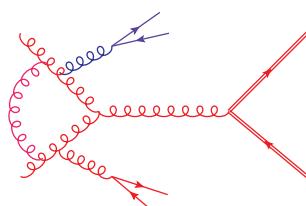


$t\bar{t}b\bar{b}g$ MEs plus PS $g \rightarrow b\bar{b}$ emission

- LO $t\bar{t}b\bar{b}g$ uncertainty $\sim 100\%$ at large p_T
- largely cancelled by PS-matching at small p_T

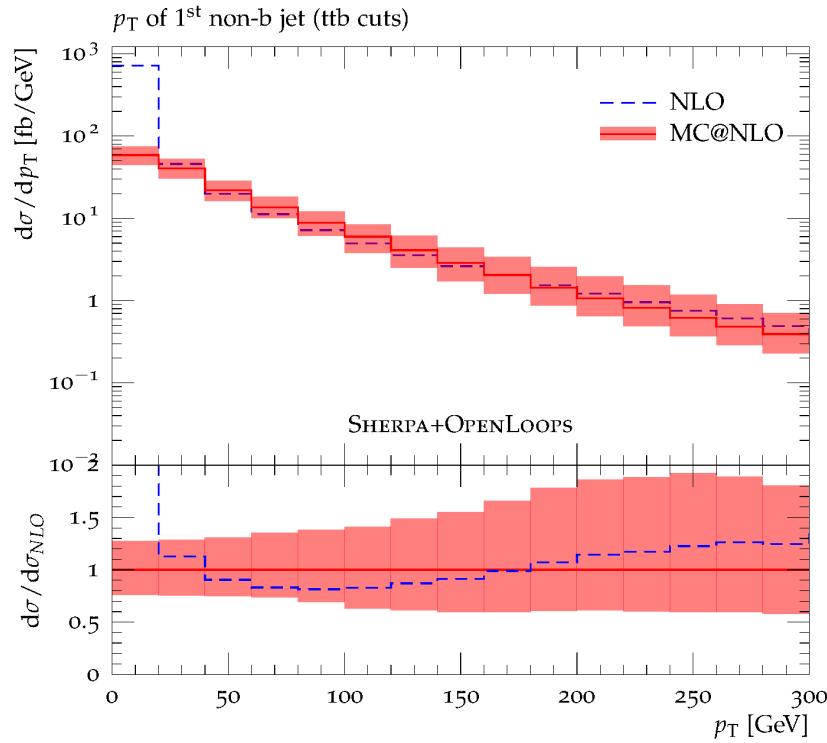
$t\bar{t}b\bar{b}$ MEs plus PS gluon and $g \rightarrow b\bar{b}$ emissions

- dominates at small p_T
- NLO $t\bar{t}b\bar{b}$ accuracy $\sim 25\text{--}30\%$



Well reflected in scale uncertainty of 1st light-jet emission on top of $t\bar{t}b\bar{b}\dots$

ttb analysis ($N_b \geq 1$): 1st light-jet p_T distribution (responsible for double splittings)



MC@NLO vs NLO

- Sudakov damping of NLO IR singularity at $p_T \rightarrow 0$
- 25% NLO excess in the hard tail (probably due to dynamic μ_Q , multi-jet final state, unresolved b-quark)

MC@NLO scale uncertainty

- LO-like uncertainty ($\sim 100\%$) in the tail irrelevant for $t\bar{t}H(b\bar{b})$
- NLO-like accuracy ($\sim 30\%$) up to 70 GeV

⇒ NLO-like accuracy in the region relevant for $t\bar{t}H(b\bar{b})$

Conclusions

OpenLoops

- handles $2 \rightarrow 2, 3, 4(5)$ SM process at NLO QCD very efficiently
- well tested, working for nontrivial LHC studies, ready for publication

Examples of first applications ($t\bar{t}b\bar{b}$ and $W^+W^-b\bar{b}$)

- $m_b > 0$ and NLO matching crucial for applicability to exp analysis and give access to new central physics aspects (unified $t\bar{t}$ and Wt description, double splittings)
- still lot to learn ~ 4 years after first NLO papers (2009, 2011) and and not yet the end of the story (double-splitting systematics in $t\bar{t}b\bar{b}$, NLOPS for $W^+W^-b\bar{b}$, ...)

Lesson

- progress greatly enhanced by NLO automation but running automated NLO tools is only the first trivial step
- high degree of realism in NLO multi-particle simulations and solid understanding of their physics content remain nontrivial and time consuming tasks

BACKUP SLIDES

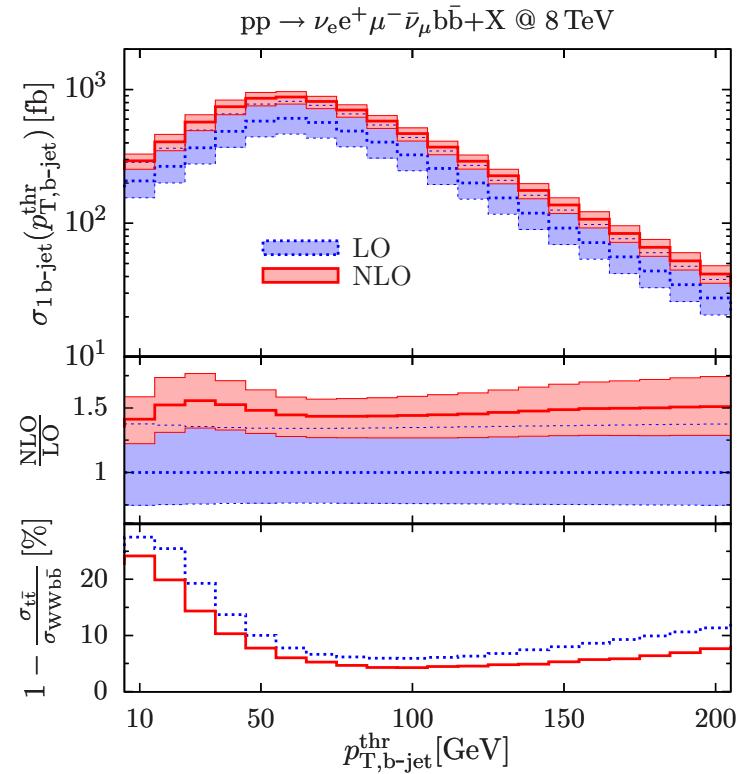
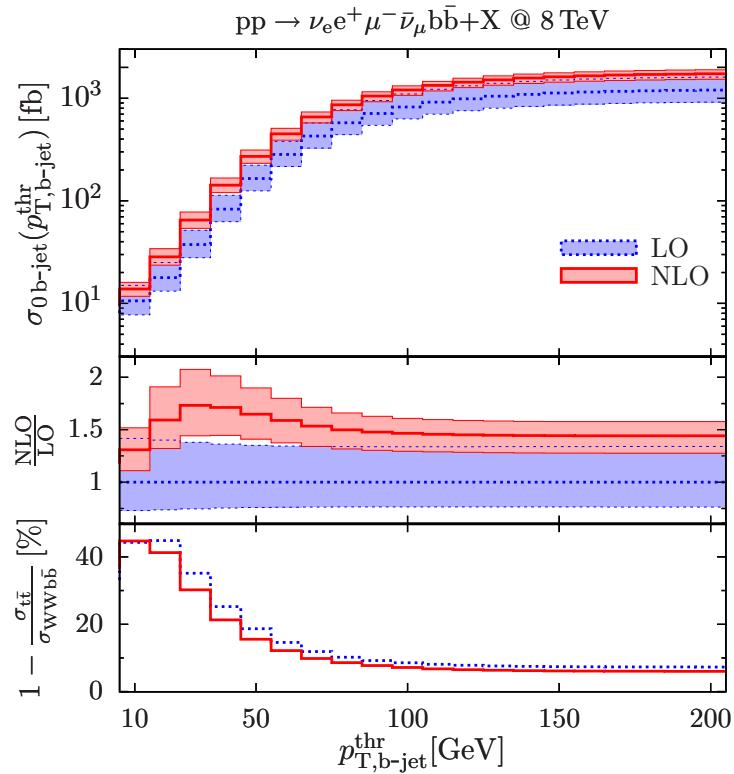
$W^+W^-b\bar{b}$ Cross Section in Generic-Jet Bins

		μ_0	$\sigma[\text{fb}]$	$\sigma_0[\text{fb}]$	$\sigma_1[\text{fb}]$	$\sigma_{2+}[\text{fb}]$
LO	μ_{WWbb}		$1232^{+34\%}_{-24\%}$	$37^{+38\%}_{-25\%}$	$367^{+36\%}_{-24\%}$	$828^{+33\%}_{-23\%}$
NLO	μ_{WWbb}		$1777^{+10\%}_{-12\%}$	$41^{+3\%}_{-8\%}$	$377^{+1\%}_{-6\%}$	$1359^{+14\%}_{-14\%}$
K	μ_{WWbb}	1.44		1.09	1.03	1.64
LO	m_t		$1317^{+35\%}_{-24\%}$	$35^{+37\%}_{-25\%}$	$373^{+36\%}_{-24\%}$	$909^{+35\%}_{-24\%}$
NLO	m_t		$1817^{+8\%}_{-11\%}$	$40^{+4\%}_{-8\%}$	$372^{+1\%}_{-8\%}$	$1405^{+13\%}_{-13\%}$
K	m_t	1.38		1.14	1.00	1.55
		μ_0	$\sigma^{\text{FtW}}[\text{fb}]$	$\sigma_0^{\text{FtW}}[\text{fb}]$	$\sigma_1^{\text{FtW}}[\text{fb}]$	$\sigma_{2+}^{\text{FtW}}[\text{fb}]$
LO	μ_{WWbb}		$91^{+41\%}_{-27\%}$	$13^{+42\%}_{-27\%}$	$71^{+40\%}_{-27\%}$	$7^{+45\%}_{-29\%}$
NLO	μ_{WWbb}		$107^{+6\%}_{-11\%}$	$13^{+1\%}_{-7\%}$	$61^{+2\%}_{-16\%}$	$33^{+51\%}_{-31\%}$
K	μ_{WWbb}	1.18		0.99	0.86	4.70
LO	m_t		$63^{+36\%}_{-25\%}$	$8^{+36\%}_{-25\%}$	$49^{+36\%}_{-24\%}$	$6^{+46\%}_{-29\%}$
NLO	m_t		$100^{+17\%}_{-16\%}$	$13^{+14\%}_{-14\%}$	$65^{+9\%}_{-12\%}$	$23^{+42\%}_{-28\%}$
K	m_t	1.58		1.47	1.32	3.89

$W^+W^-b\bar{b}$ Cross Section in b-Jet Bins

		μ_0	$\sigma[\text{fb}]$	$\sigma_0[\text{fb}]$	$\sigma_1[\text{fb}]$	$\sigma_{2+}[\text{fb}]$
LO	μ_{WWbb}		$1232^{+34\%}_{-24\%}$	$37^{+38\%}_{-25\%}$	$367^{+36\%}_{-24\%}$	$828^{+33\%}_{-23\%}$
NLO	μ_{WWbb}		$1777^{+10\%}_{-12\%}$	$65^{+20\%}_{-17\%}$	$571^{+14\%}_{-14\%}$	$1140^{+7\%}_{-10\%}$
K	μ_{WWbb}	1.44		1.73	1.56	1.38
LO	m_t		$1317^{+35\%}_{-24\%}$	$35^{+37\%}_{-25\%}$	$373^{+36\%}_{-24\%}$	$909^{+35\%}_{-24\%}$
NLO	m_t		$1817^{+8\%}_{-11\%}$	$63^{+20\%}_{-17\%}$	$584^{+14\%}_{-14\%}$	$1170^{+5\%}_{-9\%}$
K	m_t	1.38		1.80	1.56	1.29
		μ_0	$\sigma^{\text{FtW}}[\text{fb}]$	$\sigma_0^{\text{FtW}}[\text{fb}]$	$\sigma_1^{\text{FtW}}[\text{fb}]$	$\sigma_{2+}^{\text{FtW}}[\text{fb}]$
LO	μ_{WWbb}		$91^{+41\%}_{-27\%}$	$13^{+42\%}_{-27\%}$	$71^{+40\%}_{-27\%}$	$7^{+45\%}_{-29\%}$
NLO	μ_{WWbb}		$107^{+6\%}_{-11\%}$	$20^{+18\%}_{-17\%}$	$82^{+4\%}_{-10\%}$	$5^{+2\%}_{-10\%}$
K	μ_{WWbb}	1.18		1.49	1.16	0.77
LO	m_t		$63^{+36\%}_{-25\%}$	$8^{+36\%}_{-25\%}$	$49^{+36\%}_{-24\%}$	$6^{+46\%}_{-29\%}$
NLO	m_t		$100^{+17\%}_{-16\%}$	$16^{+22\%}_{-18\%}$	$77^{+16\%}_{-15\%}$	$6^{+12\%}_{-16\%}$
K	m_t	1.58		1.89	1.58	1.10

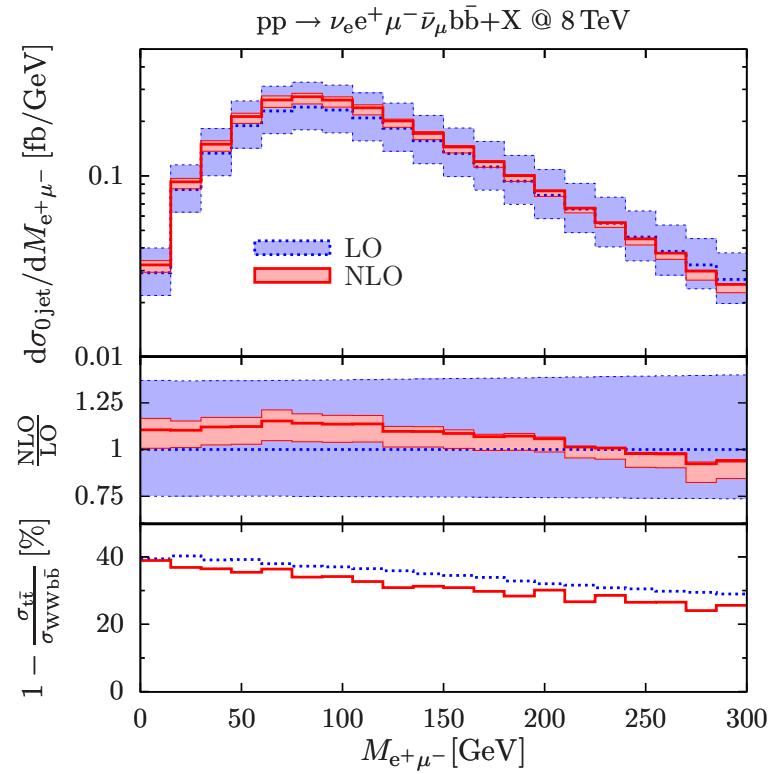
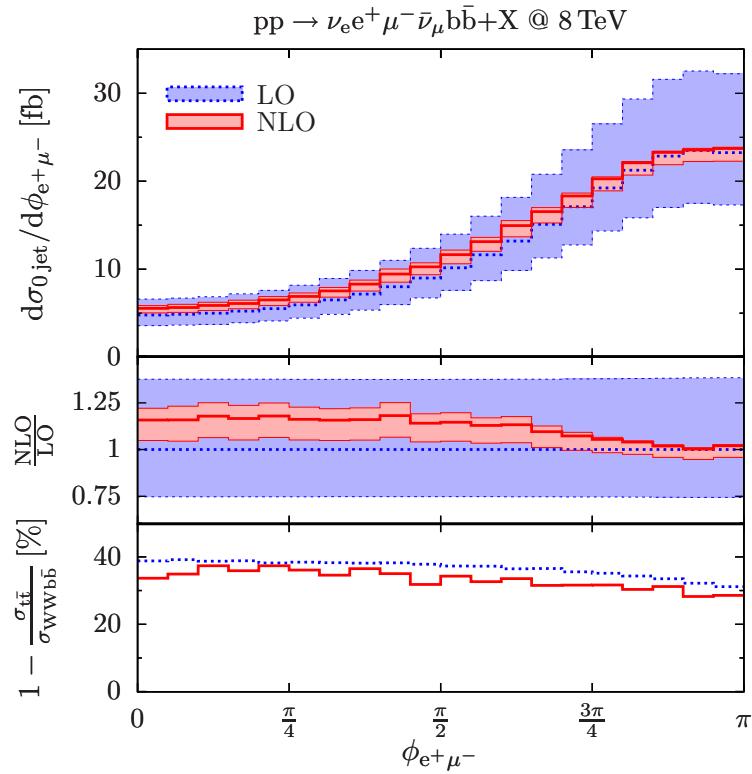
b-Jet-Veto and Binning Effects



- NLO radiation doesn't change b-jet multiplicity \Rightarrow rather stable K -factor and uncertainties
- single-top and off-shell effects still enhanced at small b-jet p_T

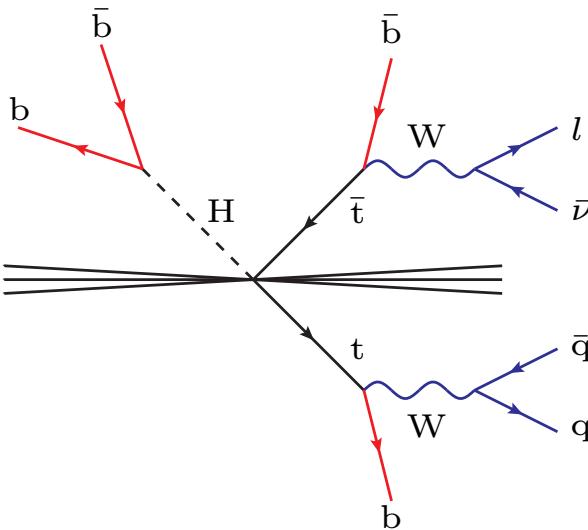
In general: nontrivial interplay of NLO and off-shell/single-top effects

$t\bar{t}$ and Wt Background to $H \rightarrow W^+W^-$ in 0-Jet Bin



- $\Delta\phi_{e^+\mu^-}$ and $M_{e^+\mu^-}$ distributions feature 10% NLO uncertainty
- significant (although moderate) NLO shape distortions
- **30–40% FtW contributions** (nontrivial $t\bar{t}/Wt$ mix)

$t\bar{t}H$ Analyses at the LHC



- *direct* probe of $t\bar{t}H$ Yukawa coupling
- $t\bar{t}H(b\bar{b})$ originally considered best discovery channel for light Higgs
- complicated $b\bar{b}b\bar{b}\ell\nu jj$ final state hampers $H \rightarrow b\bar{b}$ peak reconstruction \Rightarrow very large QCD backgrounds

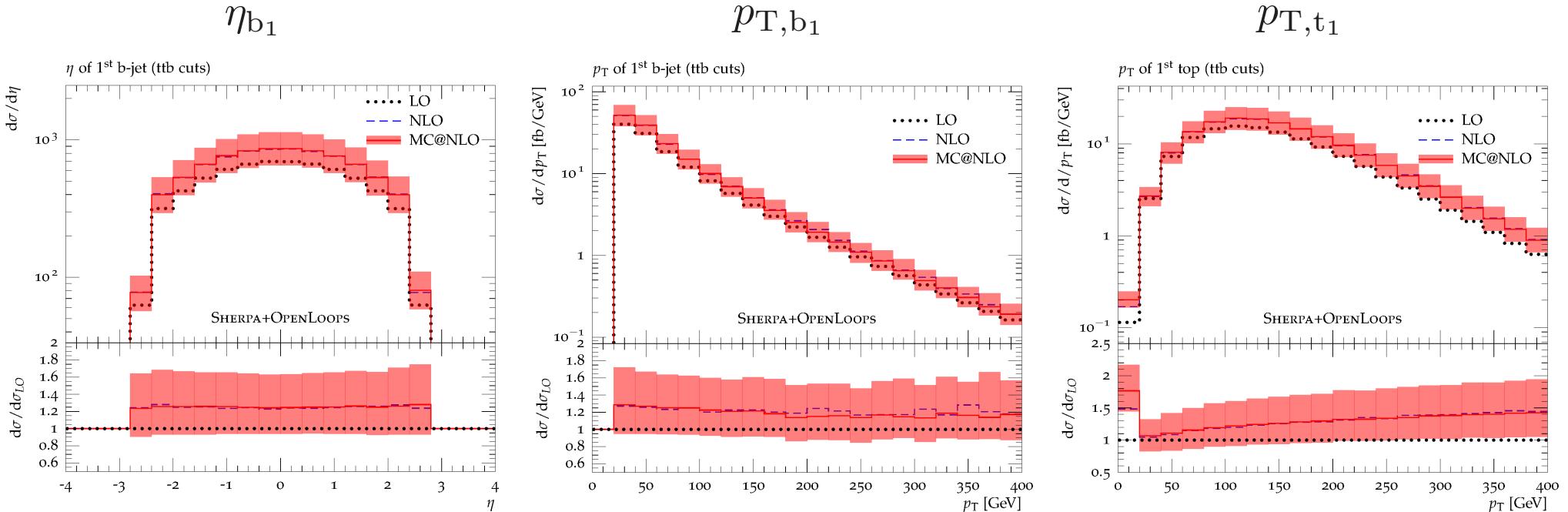
Status of $t\bar{t}H$ analyses in various channels

95% exclusion in $\sigma_{t\bar{t}H}^{\text{SM}}$ units	$H \rightarrow b\bar{b}$	$H \rightarrow VV^*$	$H \rightarrow \gamma\gamma$
ATLAS	4.1 (2.6)		4.7 (5.4)
CMS	5.2 (4.1)	6.6 (2.4)	5.3 (5.4)

- sensitivity already $\sim 100\% \lambda_t^{\text{SM}}$ and $t\bar{t}H$ searches still quite active
- expected sensitivity $\sim 10\% \lambda_t^{\text{SM}}$ with 300 fb^{-1}

NLO and MC@NLO Effects in Distributions

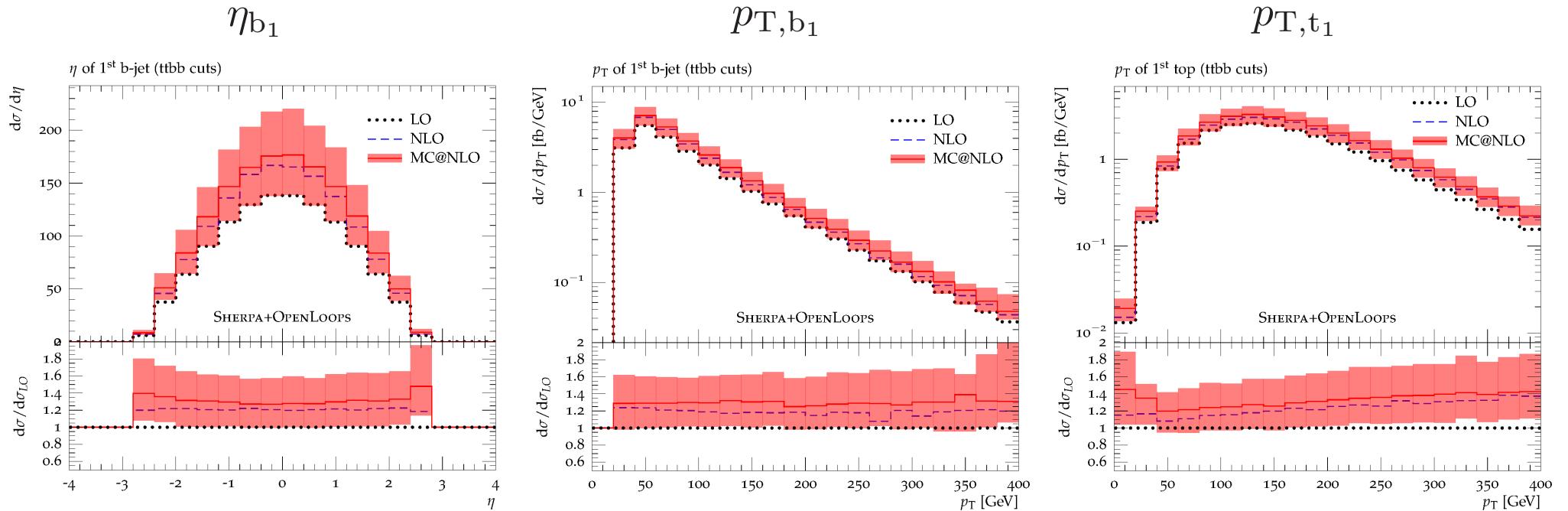
ttb analysis ($N_b \geq 1$): b-jet and top-quark distributions



Reliable perturbative prediction

- shape of 1st b-jet very stable wrt NLO corrections (thanks to dynamic scale!)
- shape of 1st top receives significant ($\sim 25\%$) NLO correction
- **excellent MC@NLO vs NLO agreement**

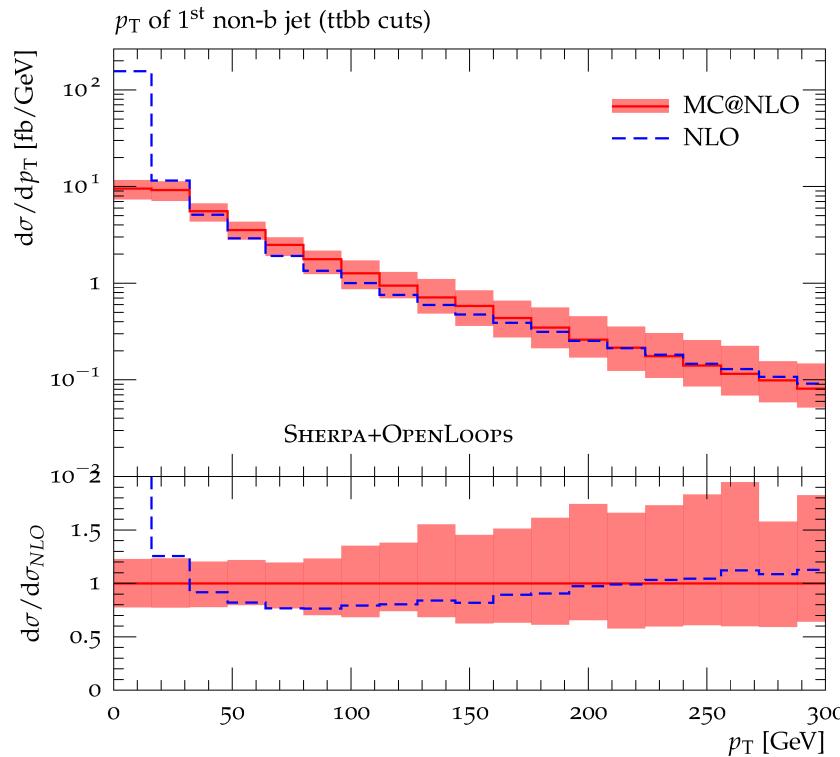
$ttbb$ analysis ($N_b \geq 2$): b-jet and top-quark distributions



Similarly good stability as for ttb analysis

- apart from moderate MC@NLO excess wrt NLO
- resulting distortions of b-jet and top distributions very mild

$t\bar{t}bb$ analysis ($N_b \geq 2$): 1st light-jet p_T distribution



MC@NLO vs NLO

- in good (5%) agreement in the tail
- Sudakov damping of NLO IR singularity at $p_T \rightarrow 0$
- $\sim 25\%$ deviation at intermediate p_T consistent with expected NNLO effect

MC@NLO scale uncertainty

- LO-like uncertainty ($\sim 100\%$) in the tail irrelevant for $t\bar{t}H(b\bar{b})$
- NLO-like accuracy ($\sim 25\%$) up to 100 GeV